TEMPERATURE AND CONCENTRATION MEASUREMENTS IN MODEL EXHAUST PLUMES USING INVERSION TECHNIQUES

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ABSTRACT

The experimental determination of temperature and pressure distribution in the high velocity gas stream encountered in a rocket engine exhaust plume is of value in gaining greater insight into the actual combustion processes occurring in the engine. The study of injector and nozzle processes is also aided by such measurement. In addition, knowledge of temperature and pressure distribution is essential for the calculation of the radiation emanating from the exhaust plume.

In the technique described herein the spectral radiance and spectral transmittance of infrared active exhaust species are measured along a series of coplanar, chordal lines of sight spanning the exhaust. The data thus obtained allow equations describing the radiant energy transferred through the exhaust to be solved either directly or by inversion methods of the radial distributions of spectral radiance and spectral emissivity. From these latter two quantities the radial distributions of temperature and partial pressure are calculated. This technique has been used to map a portion of the exhaust plume of a 1000 pound thrust rocket motor for the propellants liquid oxygen/kerosene and liquid oxygen/alcohol.

INTRODUCTION

Spectroscopic studies of the radiation produced by the combustion of rocket propellants have been made with three particular goals in mind: detection of an in-flight missile and identification of propellants from emitted electromagnetic radiation; formation of an exhaust plume model that allows calculation of emitted radiation; and determination of rocket engine performance characteristics.

The first goal requires the data obtainable from emission spectroscopy; i.e., ultraviolet, visible, and infrared emission intensities are measured as functions of wavelength for various propellants and engine sizes, and the emitting species are identified. Once sufficient information of this type is available, it should be possible to deduce the propellant and engine size from observation of the exhaust plume spectra.

The second and third goals each require the same spectroscopic techniques since the quantities to be determined in each case are temperature and species partial pressure distributions in the exhaust. It has been shown that meaningful data cannot be obtained from a single line-of-sight measurement when significant gradients exist in the exhaust. To determine the requisite quantities properly, the spectral radiance and spectral transmittance of the exhaust must be measured spectroscopically along a set of predetermined coplanar lines of sight. This measurement technique has been termed "zone radiometry" at Rocketdyne, and the work done to date is described in references 1, 2, and 3. With this type of data, the equations for radiant energy transfer through the exhaust for each line of sight may be solved simultaneously for the local values of spectral radiance and spectral emissivity. From these latter two quantities, the local values of temperature and species partial pressure may be calculated.

Temperature and pressure distributions can be obtained in this manner across various planes in an exhaust and can serve as checks on various phases of plume model calculations. Such distributions determined at the nozzle exit plane can be compared with theoretical predictions of exhaust temperatures and constituents. The mixing characteristics of various injector patterns may also be studied by zone radiometry techniques.

The prime advantage of optical spectroscopic techniques over other diagnostic techniques is that no physical contact with the hot gas stream is required. The disadvantage is that temperature and partial pressures can both be determined only for combustion products (such as CO_2, HF, H_2O, carbon particles, HCl, etc.) that possess suitable absorptive and emissive properties. It is possible to determine relative concentration distributions for "nonequilibrium" species such as OH, CH, NB, etc.

This document explains the spectroscopic technique of zone radiometry as it has been developed at Rocketdyne. Methods of calculating partial pressure and temperature distributions from line-of-sight measurements of spectral radiance and transmittance are discussed first. Experimental techniques are discussed, and finally, some typical results are presented and possible applications mentioned.

THEORY OF ZONE RADIOMETRY

From the absorptive properties of a gaseous medium, the partial pressures of the absorbing species may be determined. If the medium is at elevated temperatures, then measurement of both the radiative properties and absorptive properties allows the temperature and partial pressure to be determined. The required techniques are best understood by first considering media homogeneous in temperature and pressure, and then extending the technique to heterogeneous media.

Absorption of Radiation by Homogeneous Gaseous Media

The extent to which a gaseous medium absorbs incident radiation depends principally upon the wavelength, λ, of the radiation, the density and identity of the molecular species in the gas, and the optical path length, L, in the medium. These parameters are related by the equation

$$\tau(\lambda) = e^{-K(\lambda, T) PL} = 1 - \alpha(\lambda) = 1 - \epsilon(\lambda), \qquad (1)$$

where P is the partial pressure of the absorbing gas. The quantity $K(\lambda, T)$ is called the spectral absorption coefficient and, for a given wavelength and temperature, is a unique property of the absorbing gas. The temperature dependence is small compared to the wavelength dependence. The quantity $\tau(\lambda)$ is the spectral transmissivity (fractional transmittance), $\alpha(\lambda)$ is the spectral absorptivity, and $\epsilon(\lambda)$ is the spectral emissivity; $\alpha(\lambda) = \epsilon(\lambda)$ for a medium in thermodynamic equilibrium.

In a laboratory absorption experiment the gas to be studied is contained in an absorption cell at known temperature and pressure. Radiation from a continuum source, $I_o(\lambda)$, is sent through the cell by suitable optics.

The radiation transmitted by the gas and the cell windows, $I(\lambda)$, is detected and recorded. By making the same measurement with the cell evacuated, the background spectrum, $I_o(\lambda)$, may be recorded. The absorption spectrum (percent transmission as a function of wavelength) is obtained from the simple relation $\tau(\lambda) = I(\lambda)/I_o(\lambda)$. In this type of experiment, P and L are known, and $K(\lambda, T)$ can be calculated from Equation (1). By performing this experiment over a range of temperatures, $K(\lambda, T)$ can be completely determined for a particular species.

The effect of any variation in $K(\lambda, T)$ over the wavelength interval encompassed by the spectral band pass of the instrument must be considered in these experiments. This effect will be discussed later.

The spectroscopic method of pressure determination makes use of the fact that once $K(\lambda, T)$ has been determined for various species by the method outlined above, then the pressure of an unknown gas concentration can be determined from Equation (1) by measurement of $\tau(\lambda)$, T, and L. The identity of the gas is determined from its absorption spectrum. When the medium under study contains a mixture of gases, then measurements at a particular wavelength yield the partial pressure of a particular species.

This technique of pressure determination is restricted to gases which do possess an absorption spectrum. Generally, any gas whose molecules contain at least two dissimilar atoms will have an absorption spectrum. For a gas in thermodynamic equilibrium, absorption and emission of radiation occur in identical wavelength regions, so that the above restriction will also apply to the spectral radiance measurements discussed below. Generally, different species absorb (and emit) in different wavelength regions, although some overlap may occur.

Spectral Radiance. The intensity of radiation emanating from a gaseous medium is most conveniently measured in terms of the amount of energy per unit wavelength interval leaving a unit area of the gas surface and filling a given solid angle. This quantity is called "spectral radiance" and may be expressed in units of watts cm^{-2} $steradian^{-1}$ $micron^{-1}$.

Spectral radiance is most simply measured by comparing the brightness of the hot gas with the brightness of a standard source at known temperature, such as a blackbody. The optical system and the monochromator serve to ensure that the detector is viewing the same solid angle, area of the source, and wavelength interval, whether viewing the hot gas or the blackbody. In this manner, the spectral radiance of the hot gas will be equal to that of the blackbody if the detector produces the same output signal whether viewing one source or the other. In this situation, the gas and the blackbody have the same "brightness temperature" but not the same true temperature. (Any emission from the cell windows must be taken into account.)

The spectral radiance of a blackbody $N_{BB}(\lambda, T)$ is a unique function of wavelength and temperature, and is given by the expression

$$N_{BB}(\lambda, T) = \frac{C_1}{\lambda^5} \left(\epsilon^{-C_2}/\lambda T - 1\right), \tag{2}$$

where C_1 and C_2 are known constants. The blackbody source itself must periodically be temperature-calibrated with an optical pyrometer.

Temperature. The spectral radiance of the gas, $N(\lambda)$, is related to the spectral radiance produced by a blackbody which is at the same temperature, T_g, as the gas, by the expression

$$N(\lambda) = N_{BB}(\lambda, T_g)/\epsilon(\lambda), \tag{3}$$

where $\epsilon(\lambda)$ is the spectral emissivity as determined by Equation (1). Thus, once $N(\lambda)$ and $\epsilon(\lambda)$ have been measured, the quantity $N_{BB}(\lambda, T_g)$ can be calculated from Equation (3), and the gas temperature is then uniquely determined from Equation (2), since T_g is now the only unknown quantity in that expression.

MEDIA CONTAINING CONCENTRATION AND TEMPERATURE GRADIENTS

The spectroscopic technique of pressure determination described above is of particular value in analyzing a system consisting of several gases that are intermixing while traveling at high velocity. If the gases are high-temperature combustion products, then their temperature also must be determined spectroscopically. For a medium which contains concentration and temperature gradients, the expressions for the transmissivity and the radiance along a particular line of sight must be written in terms of integrals along that line of sight. With reference to Figure 1, consider a particular plane passing through the medium and perpendicular to the gas-flow axis. It must be assumed that conditions across this plane are fixed in time for the duration of the measurements. The fraction of incident radiation transmitted along a line of sight parallel to the y axis would be given by

$$\tau_{\lambda,x} = \epsilon^{-\int_{y_1}^{y_2} K_{\lambda,T} P(x,y)dy}. \tag{4}$$

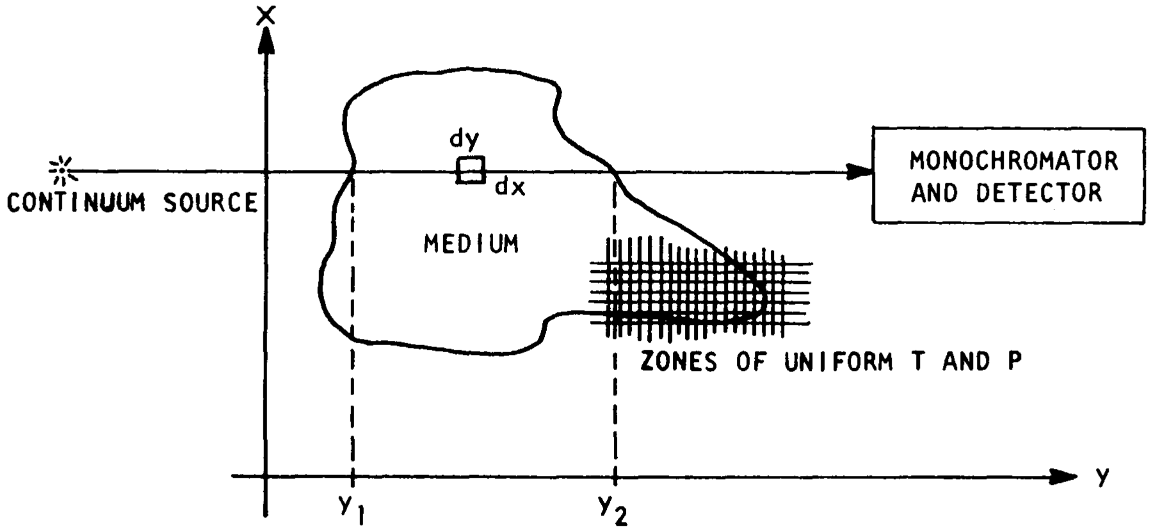

FIGURE 1. CROSS SECTION OF MEDIUM CONTAINING CONCENTRATION AND TEMPERATURE GRADIENTS

If $N_\lambda (x,y)$ is a local value of the radiance per unit path length, then $N_\lambda (x,y)dy$ is the amount of radiance leaving a small-volume element parallel to the x axis. This radiance will be attenuated by the gas between the volume element and y_2. Thus, the actual amount of radiance from a single-volume element that escapes the medium is given by

$$N_\lambda (x,y)dy \ \epsilon^{-\int_y^{y_2} K_{\lambda,T} P(x,y)dy}.$$

The value of spectral radiance that would actually be measured for a particular line of sight is thus given by

$$N_{\lambda,x} = \int_{y_1}^{y_2} N_\lambda (x,y) \left[\epsilon^{-\int_y^{y_2} K_{\lambda,T} P(x,y)dy} \right] dy . \tag{5}$$

Equations (4) and (5) express quantities which may be measured, $\tau_{\lambda,x}$ and $N_{\lambda,x}$, in terms of the unknown quantities $[K_{\lambda T} P(x,y)]$ and $N_\lambda (x,y)$. It should be understood that any attempt to calculate a temperature and pressure from values of $\tau_{\lambda,x}$ and $N_{\lambda,x}$ obtained at a single line of sight and wavelength for a heterogeneous medium would yield "some sort of average" temperature and pressure, and these average values would be essentially meaningless.

In the most general case, Equations (4) and (5) would be solved in the following manner. A particular plane of the medium is assumed to be divided into a matrix of M zones (hence, the term "zone radiometry") of uniform size. The zones are small enough so that the temperature and pressure in each zone may be assumed to be uniform, and the variation between adjacent zones is small. Equations (4) and (5) may then be replaced by the appropriate summation expressions. The line-of-sight quantities τ_λ and N_λ must each be measured at the same wavelength along M different lines of sight, with each zone being traversed at least once. A number equal to the $\sqrt{M}$ line of sight can be made parallel to the y axis, an equal number parallel to the x axis, and the remaining number can be at various angles to the y axis. These measurements of M values of τ_λ furnish a set of M simultaneous equations of the form of Equation (4) which can be solved for M values of the product $\left[K_{\lambda,T} P(x,y)\right]$ for each of the M zones. The M values of $\left[K_{\lambda,T} P(x,y)\right]$ obtained from the transmission measurements are used with the M measured values of N_λ in a set of simultaneous equations of the form of Equation (5). These equations can be solved for N_λ (x,y).

The value of the emissivity for each zone is calculated from the expression

$$\epsilon_\lambda (x,y) = 1 - \epsilon^{-K_{\lambda,T} P(x,y)a},$$

where a is the zone width along the line of sight. As discussed previously, the temperature of each zone is defined by the equation

$$N_{BB} [\lambda, T_g (x,y)] = \frac{N_\lambda (x,y)}{\epsilon_\lambda (x,y)} . \tag{7}$$

Once the zonal temperature has been determined, a value of $K_{\lambda,T}$ can be assigned to each zone, and the zonal partial pressure can be calculated as before.

One set of absorption and emission measurements, as described above, allows the temperature and pressure distribution to be determined across a single plane in the medium. By performing the measurements across a series of planes, temperature and pressure profiles for the entire flow field can be obtained.

Effect of Symmetry. If the flow field under study possesses symmetry, then the number of lines of sight required to determine the temperature and pressure distributions can be considerably reduced. Since as many as 100 zones might be required to describe a particular flow field properly, it is of value to recognize any symmetry that is present. For example, if two symmetry planes are present, then 25 lines of sight would be sufficient to obtain the data necessary for solving a 100-zone flow field problem. Radially symmetric flow fields which are often encountered, are the most convenient to analyze and handle experimentally. In the work done at Rocketdyne [1, 2, and 3], the rocket exhausts studied all possessed radial symmetry. In this case, the zones of uniform temperature and pressure and corresponding lines of sight are chosen as shown in Figure 2, and Equations (4) and (5) become

$$\tau_{\lambda,x} = e^{-\int_{-y_o}^{y_o} K_{\lambda,T} P_r dy} \tag{8}$$

$$N_{\lambda,x} = \int_{-y_o}^{y_o} N_r e^{-\int_{-y_o}^{y_o} K_{\lambda,T} P_r dy} dy. \tag{9}$$

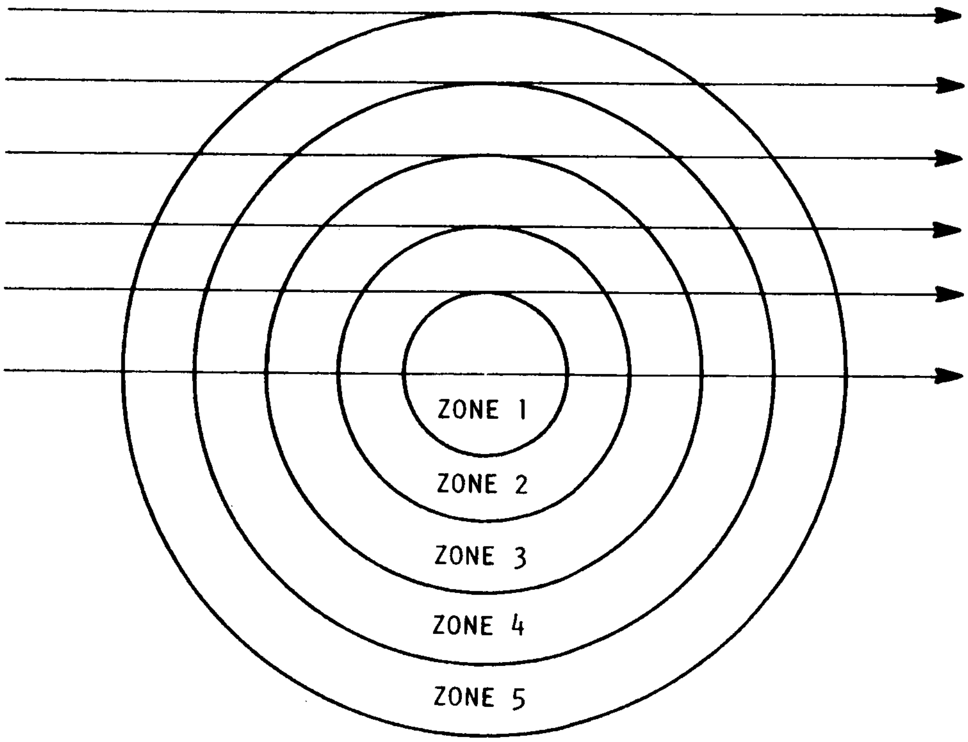

FIGURE 2. LINES OF SIGHT FOR RADIALLY SYMMETRIC FLOW FIELD

Two methods have been used to solve these equations. The first follows the method outlined by Freeman and Katz [4] and makes use of the Abel integral equation. This equation is

$$F(x) = 2 \int_{x}^{r_o} G(r) \quad (r^2 - x^2)^{-\frac{1}{2}} \; rdr, \tag{10}$$

and has its solution

$$G(r) = -\frac{1}{\pi} \int_{r}^{r_o} \frac{dF(x)}{dx} (x^2 - r^2)^{-\frac{1}{2}} dx. \tag{11}$$

Freeman and Katz [4] show how to place Equations (8) and (9) in the form of Equation (10). Their technique requires the expansion of the exponential in Equation (9) and the retention of only certain terms. This approximation limits the use of this method to the study of flows which have a maximum absorption along any one line of sight of about 30 percent. Equation (11) has been treated in numerous ways. In Nestor and Olsen's treatment [5], the resulting expressions are

$$[K_{\lambda,T}P]_K = -\frac{2}{\pi a} \sum_{n=K}^{N} \left(\mathrm{Ln}\,\frac{1}{\tau_n}\right) B_{Kn} \tag{12}$$

$$N_K = -\frac{2}{\pi a} \sum_{n=K}^{N} \frac{2N_n}{1 + \tau_n} B_{Kn} \tag{13}$$

for the solutions of Equations (8) and (9). The subscript n refers to the nth line of sight and K refers to the Kth zone; a is the zone width. The elements in the matrix B_{Kn} are tabulated in reference 5 .

The above method was used in the program described in reference 3 in which the rocket motors were operated at simulated altitude and the maximum absorption along any line of sight was less than 35 percent.

A second method was used to solve Equations (8) and (9) for the work described in reference 2 , where the motors were operated at sea level and the exhaust plume was optically thick in various wavelength regions. This method is simply to solve the set of equations of the form of Equation (8) simultaneously by back substitution. The radial values of the product $K_{\lambda,T}P_r$ thus obtained are then used in the set of equations of the form of Equation (9) which are also solved by back substitution. Back substitution means that $K_{\lambda,T}P_N$ and N_N for the outermost zone are obtained directly from data taken along the line of sight through that zone (Nth line-of-sight).

These results are then used with the data taken along the (N-1)th line of sight to obtain $K_{\lambda,T}P_{N-1}$ and N_{N-1}. In this manner the complete problem may be solved.

The methods of obtaining the line-of-sight radiance and transmittance values are independent of the method of solution of the resulting equations. These experimental details are covered in the next section. It should be remembered that in order to use zone radiometry for a complete temperature and partial pressure determination, it is necessary that the species under study be in local thermodynamic equilibrium. This requirement has the effect of limiting the complete zone radiometry treatment to species which are active in the infrared spectral region. It is, however, possible to obtain relative concentration distributions for species that radiate in the ultraviolet and visible spectral regions but absorb little or none of this radiation.

EXPERIMENTAL DETAILS

Measurements

To provide the required line-of-sight radiance and transmittance data, the ideal infrared instrumentation system must be able to allow performance of the following experiments:

1. Measure plume spectral radiance by comparing plume intensity with blackbody intensity; radiation is optically chopped between the plume and the detector.

2. Measure plume spectral transmittance by locating a greybody source on the opposite side of the plume from the spectrometer; greybody radiation is optically chopped between the greybody and the plume (preferably) so that the plume transmittance may be directly determined.

3. Provide for variation of line of sight by spatially scanning the images of the plume, greybody, or blackbody that are formed at the entrance slit of the spectroradiometer.

4. Obtain both radiance and absorptance measurements at several different, but accurately reproducible, wavelengths during each individual motor firing.

The method for carrying out these experiments would depend on engine test duration and engine size. For the programs described in references 1, 2, and 3 the nozzle exit diameter ranged from 4 to 8 inches and the test duration was normally 20 seconds.

Figure 3 shows the emission-absorption experimental arrangement. The greybody (absorption source) consists of an electrically heated carbon rod six inches in length mounted in an airtight, argon-purged housing. The greybody is mounted inside a 400 cps cylindrical "squirrel cage" optical chopper. Calcium fluoride windows 0.375 inch thick and 6.5 inches in diameter isolate various portions of the optical path. The three gate valves in the optical path which act as safety shutters are sequenced to open just after motor ignition and to close just before motor cutoff. The entire system may be purged with nitrogen to minimize atmospheric absorption. The diffuser was not used in the work described in reference 2.

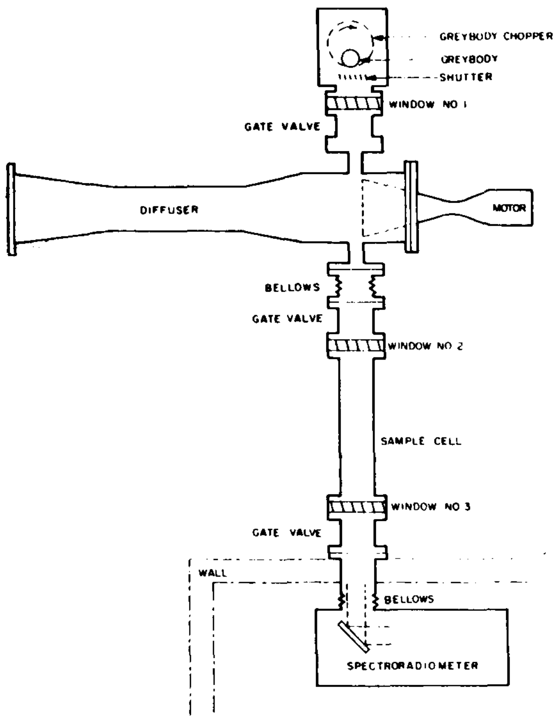

FIGURE 3. EXPERIMENTAL ARRANGEMENT FOR ABSORPTION-EMISSION MEASUREMENTS

The images of the blackbody, greybody and/or plume that are formed at the monochromator entrance slit are spatially scanned in the following manner. A cam which is rotated at constant angular velocity drives a rod at constant linear velocity up and down in front of, and in a plane parallel to, the entrance slit. This rod, called the zone ranger, contains a small aperture (subtending approximately 0.1 the plume image diameter) which limits the field of view at the plume to 1 cm x 0.2 cm (the smaller dimension depends on the slit width). Thus, this device is essentially a travelling field stop. The size of this aperture is adjustable.

During zone radiometry experiments, a filter wheel, in conjunction with a diffraction grating blazed at 30 microns, provides for wavelength selection and accurate reproducibility. A grating with a blaze wavelength of 30 microns was chosen because radiation diffracted by this grating at the blaze angle in high orders falls into spectral regions suitable for the required radiance and emissivity determinations. For instance, at the blaze angle, this grating will diffract 4.29 μ energy in seventh order to the detector, thus allowing a determination of the CO_2 (gas) radial temperature distribution; similarly, in the nineteenth order, 1.58 μ energy will be diffracted to the detector, thus allowing a determination of carbon particle radial temperature distribution. In this method each desired spectral order is isolated by a narrow band pass spectral filter, while the 30 μ blaze grating is held fixed at the blaze angle. Four filters are used in each motor firing, and the fact that the grating remains fixed insures an extremely accurate wavelength reproducibility for the absorption and emission measurements. The grating is used at the blaze angle to insure that sufficient energy is diffracted into the desired spectral orders.

Operation of the zone ranger and filter wheel, as well as the change from tuning fork chopper to greybody chopper, is automatic. A schematic of the control system is shown in Figure 5. The shaft of the zone ranger cam holds three electrical cams. One electrical cam produces a signal on the recorder event pen to key the zone ranger position. The second electrical cam momentarily disengages the filter wheel positive stop mechanism as the third activates the filter wheel stepping motor. The four-position filter wheel also produces an electrical signal on the recorder during its motion for positive filter identification. The filter wheel is activated after each zone ranger cycle. The filter wheel 30-degree stepping motor drives the filter wheel through a 3:1 gear reduction. Thus, the filter wheel makes three revolutions while the stepping motor makes one revoltuion. After the filter wheel has made one revolution, the wafer switch activates relays which in turn remove power from the tuning fork chopper, switch the 400 cps reference signal from the tuning fork chopper to the greybody chopper, and then open the greybody optical shutter.

Figure 4 shows schematically the infrared spectroradiometer. A Perkin Elmer Model 98G grating monochromator is used with either an uncooled PbS detector or a liquid nitrogen cooled PbSe detector, or a photomultiplier tube. The internal optical chopper used to chop plume emission is located just inside the monochromator exit slit. This chopper is basically a tuning fork with chopper blades attached to the tines. The tuning fork is electrically driven at the desired chopping frequency (400 cps) when plume spectral radiance is being measured. When plume absorptance is to be measured power is removed from the tuning fork driving mechanism, the tines stop in an open position in approximately one second, and the greybody optical shutter is opened to allow the chopped greybody radiation to pass through the plume.

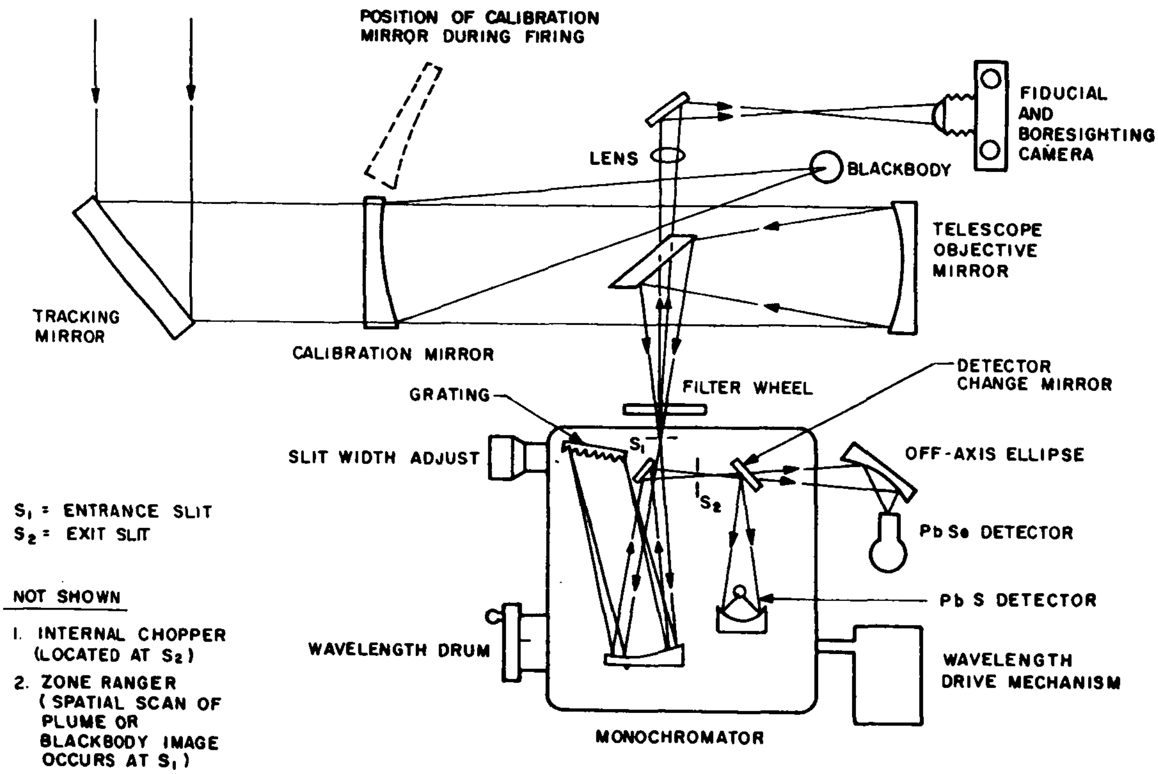

FIGURE 4. OPTICAL DIAGRAM OF INFRARED SPECTRORADIOMETER

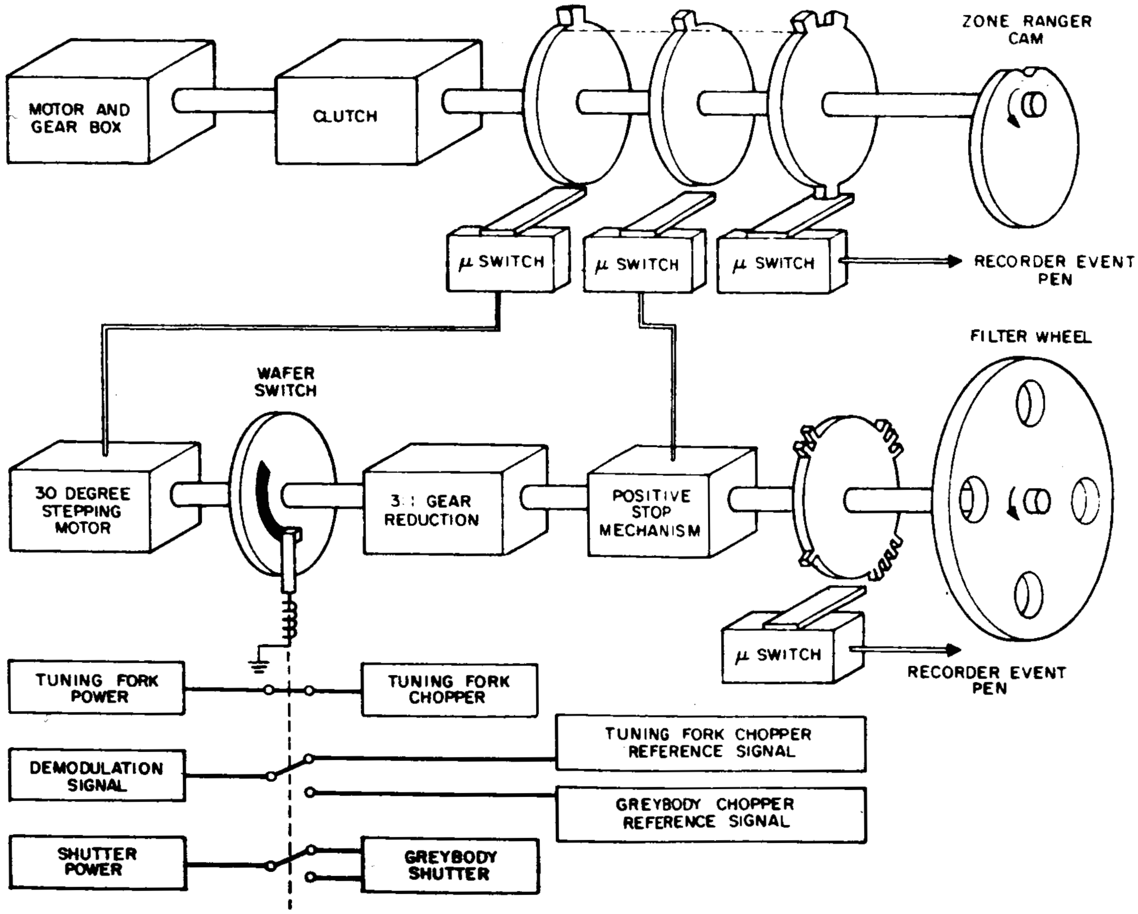

FIGURE 5. SCHEMATIC OF ZONE RANGER CONTROL SYSTEM

Approximately 20 seconds were available for the gathering of data during each motor firing. Spatial scans of the plume in emission and absorption were obtained in the following manner:

1. Before motor firing, the internal and greybody choppers are activated, the greybody is set at a desired brightness temperature, and the filter wheel is positioned so that filter No. 1 is in the optical train and so that the wafer switch relays have closed the greybody shutter, supply power to the tuning fork chopper, and allow the tuning fork 400 cps reference signal to reach amplifiers.

2. After motor ignition, the zone ranger mechanism is activated manually (all following operations then occur automatically). The zone ranger scans the plume image radius in one direction in one second. After the zone ranger makes a complete cycle (scans the plume image radius twice) the electrical cams activate the filter wheel stepping mechanism; the filter wheel makes one-quarter of a revolution, allowing energy at a second wavelength to reach the detector. The zone ranger continues to run at a half cycle per second.

3. After the filter wheel has made a complete revolution (plume radiance will have been measured at four wavelengths), the wafer switch activates relays as described above, and the zone ranger now scans at four identical wavelengths the chopped greybody radiation that is transmitted by the plume.

4. For intensity calibration purposes, the greybody and blackbody images are similarly scanned before and after each firing.

For much of the work described in reference 2, two pairs of identical filters were used in the filter wheel so that two complete sets of data were obtained at each of two wavelengths during a single firing.

Conventional spectral scans of plume emission or absorption can also be made. In this case the zone ranger device and the filter wheel are removed from the instrument. For the 1 to 2 μ range, a grating blazed at 1.6 μ is used in first order, and higher orders are eliminated by a silicon window. A grating blazed at 4 μ is used in the 2-6 μ spectral region in first order. Below 3.5 μ, higher orders are eliminated by a germanium window and above 3.5 μ by an indium arsenide window. Ultraviolet-visible spectra were obtained in the 2500 to 5000 Angstrom range using an RCA 7200 photomultiplier and grating blazed at 3000 Angstroms.

Data Reduction

Zone radiometry data were recorded on a strip chart recorder. Line-of-sight values (corresponding to pen deflection) of unattenuated greybody radiation, greybody radiation attenuated by the plume, blackbody radiation and plume radiation (all for the same line of sight) were read from the strip charts and served as input data for the computerized data reduction procdures. The computer calculated the radial values of spectral radiance, spectral emissivity, temperature, and the product $K_{\lambda, T}P_K$. For the species CO_2, values of $K_{\lambda, T}$ were taken from the work of Malkmus [6]. The product $K_{\lambda, T}P_K$ for each zone is divided by the value of $K_{\lambda, T}$ (based on the temperature of each zone) to determine the CO_2 partial pressure, P_K, for each zone.

The carbon particle density was determined in the following manner. As described in reference 2, samples of carbon particles were extracted from various portions of a LO_2/RP-1 exhaust, and the particle size distribution was determined from photomicrographs of the samples. The size distribution, along with the local values of spectral emissivity determined from zone radiometry, allowed computation of the local density of carbon particles from the theoretical curves of Stull and Plass [7] which plot spectral emissivity as a function of density for various size distributions.

RESULTS AND DISCUSSION

Figures 6, 7, and 8 are taken from reference 2. The results in these figures were obtained from data taken during ten 20-second-duration LO_2/RP-1 firings of a 1000-pound-thrust, 1000 psi chamber pressure, model of the F-1 rocket engine. The exhaust plume was assumed to be divided into concentric rings of width 0.45 cm.

Figure 6 shows that the species CO_2 is fairly evenly distributed across the exhaust plume at the nozzle exit plane and 2 inches downstream. However, 8 inches downstream the CO_2 partial pressure has risen considerably; this pressure rise is expected since this latter station is approximately 2 inches behind the first shock. Figure 7 shows the carbon particles to be concentrated within a ring at the outer edges of the plume. Presumably the carbon particles are formed in the cooler, fuel-rich combustion region along the chamber walls, and remain so distributed until they are several inches downstream. Figure 8 shows a cool central plume core at the nozzle exit plane (attributed to the injector pattern) and a sharp rise in temperature behind the first shock. The apparent existence of CO_2 and carbon particles at the nozzle exit plane a distance of several zones outside the nozzle edge is attributed to the field of view of the zone radiometer at the plume (about 1.5 cm in height). This effect, which is identical to that arising when a spectrometer scans a narrow spectral line, causes the carbon particle distribution to be considerably broader and less sharp than the true distribution. No attempt was made to correct for this broadening effect, although it would not be difficult to do so.

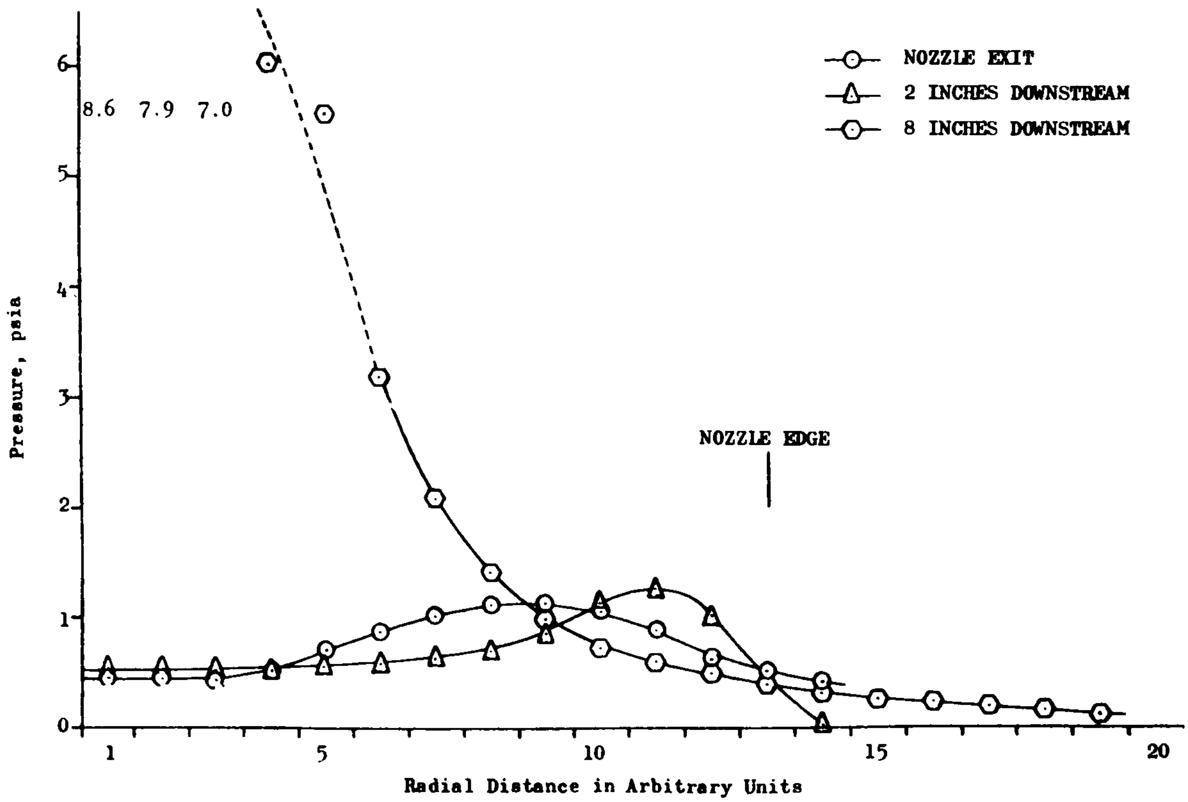

FIGURE 6. RADIAL DISTRIBUTION OF CO_2 PARTIAL PRESSURE, MODEL F-1, LO_2/RP-1

It is difficult to determine the absolute accuracy of the zone radiometry technique since there is no independent, more accurate technique of measuring the temperature or pressure in the exhaust. However, it can be said that the values obtained are reasonable; the measured CO_2 partial pressures at the nozzle exit are bounded by the theoretically predicted values of frozen and shifting equilibrium; there is fair agreement between CO_2 and carbon particle densities as measured spectroscopically and by sampling techniques. Temperature determinations made during different portions of a single run or during different runs with the same motor operating parameters showed reproducible results to within 100 degrees Kelvin.

As long as the assumption that gradients are small within individual zones is valid, the method of equation solution (inversion or simultaneous) introduces no errors into the data. In fact, one set of data with maximum line-of-sight transmittance of about thirty percent were reduced using both methods; the results were essentially identical.

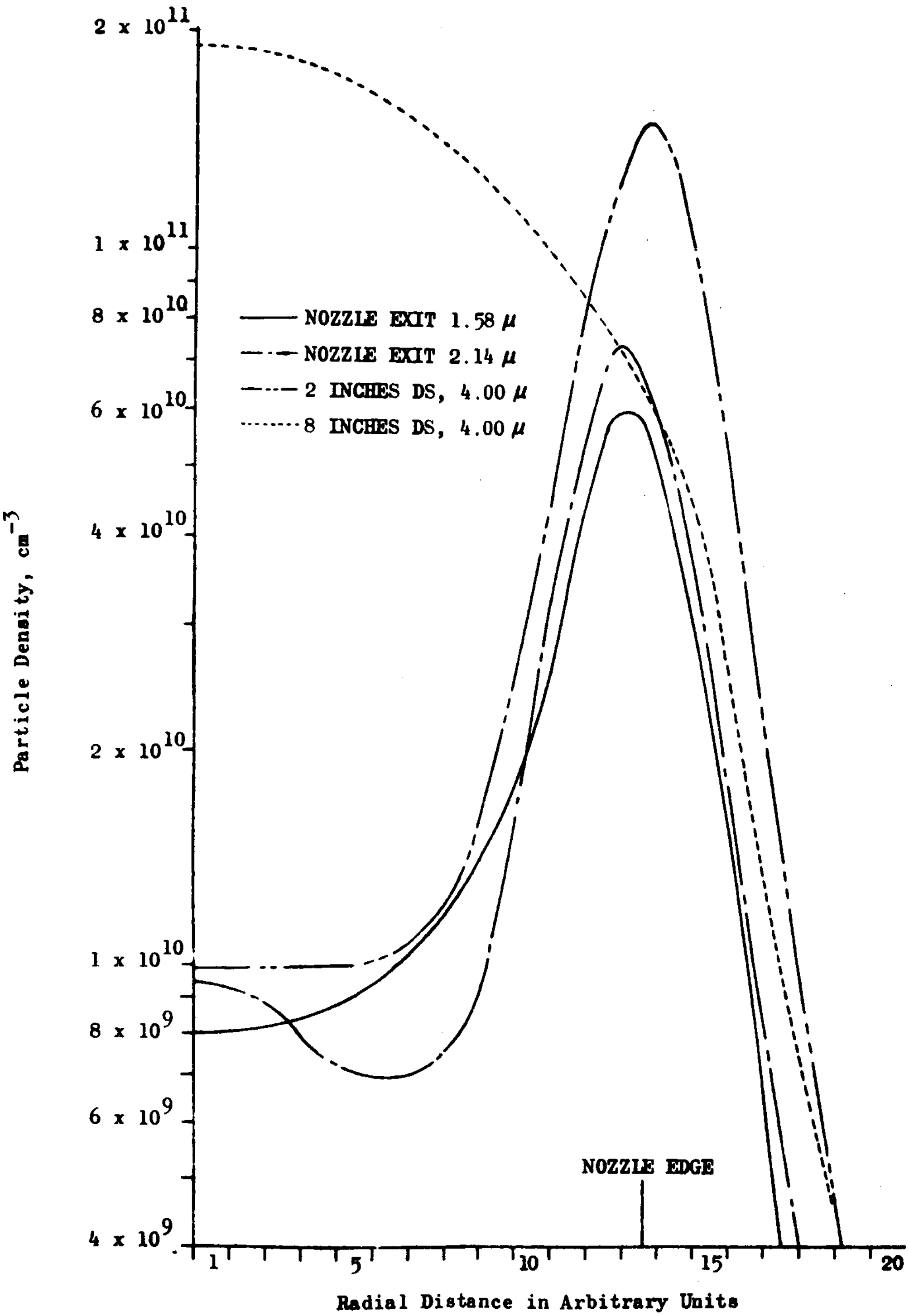

FIGURE 7. RADIAL DISTRIBUTION OF CARBON PARTICLE DENSITY, MODEL F-1, LO_2/RP-1

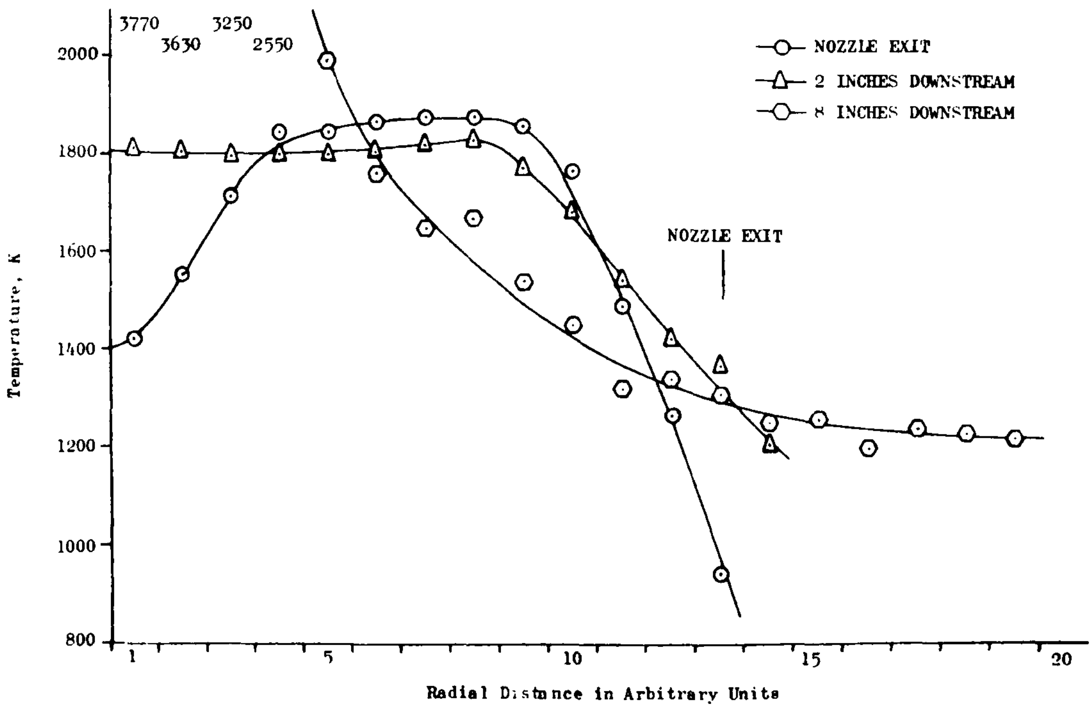

FIGURE 8. RADIAL DISTRIBUTION OF CO_2 TEMPERATURE, MODEL F-1, LO_2/RP-1

In the work to date, it has been possible to make temperature and pressure calculations only for the species CO_2 and carbon particles. The primary reason for this is that radiation from these species can be treated as continuum radiation over the spectral band pass of the spectrometer. In addition, there is considerable experimental and theoretical data available on these species. With the large amount of data that are now becoming available on H_2O and with the use of band model techniques, there should be no great problem in determining water partial pressures and concentrations.

Zone radiometry techniques are applicable to the study of any gas system. To study large rocket engine exhausts, an instrument is being developed (Contract NAS8-21144) that will use multiple absorption sources and a rotating mirror to achieve spatial scanning of the exhaust. Another instrument that is planned for the study of millisecond duration tests at Cornel Aeronautical Laboratory will image a plane in the flow field onto a detector array to achieve spatial resolution. One particular experiment that Rocketdyne hopes to carry out in the future is of interest because it will afford a check on the absolute accuracy of zone radiometry. In this experiment, partial pressures would be determined for a cold flow of premixed non-reacting gases exhausted to the atmosphere at ambient pressure. Since the concentration and total pressure of the species are known, an absolute check on absorption zone radiometry will be obtained.

REFERENCES

1. Herget, W. F.; Schumacher, P. E.; Enloe, J. D.; Levin, B. P.; and Suarez-Alfonso, E.: An Instrumentation System to Study Rocket Exhaust Plume Radiative Processes. Rpt. R-6288. Rocketdyne, a Division of North American Rockwell Corporation, Canoga Park, California, Contract No. NAS8-11261, August 27, 1965.

2. Herget, W. F.; Schumacher, P. E.; Cline, G. L.; and Ford, W. M.: Radiative and Structural Characteristics of Rocket Engine Exhaust Plumes. Rpt. R-6742. Rocketdyne, a Division of North American Rockwell Corporation, Canoga Park, California, September 29, 1966.

3. Herget, W. F.; Schumacher, P. E.; and Enloe, J. E.: Radiative Properties of Rocket Exhausts at Simulated Altitudes. Rpt. R-6347. Rocketdyne, a Division of North American Rockwell Corporation, Canoga Park, California, Contract AF08 (635)-4385, October 1966, SECRET.

4. Freeman, M. P.; and Katz, S.: J. Opt. Soc. Am., vol. 50, 1960, p. 826.

5. Nestor, O. H.; and Olsen, H. N.: SIAM Review, vol. 2, 1960, p. 200.

6. Malkmus, W.: J. Opt. Soc. Am., vol. 53, 1963, p. 951.

7. Stull, R.; and Plass, G.: J. Opt. Soc. Am., vol. 50, 1960, p. 121.